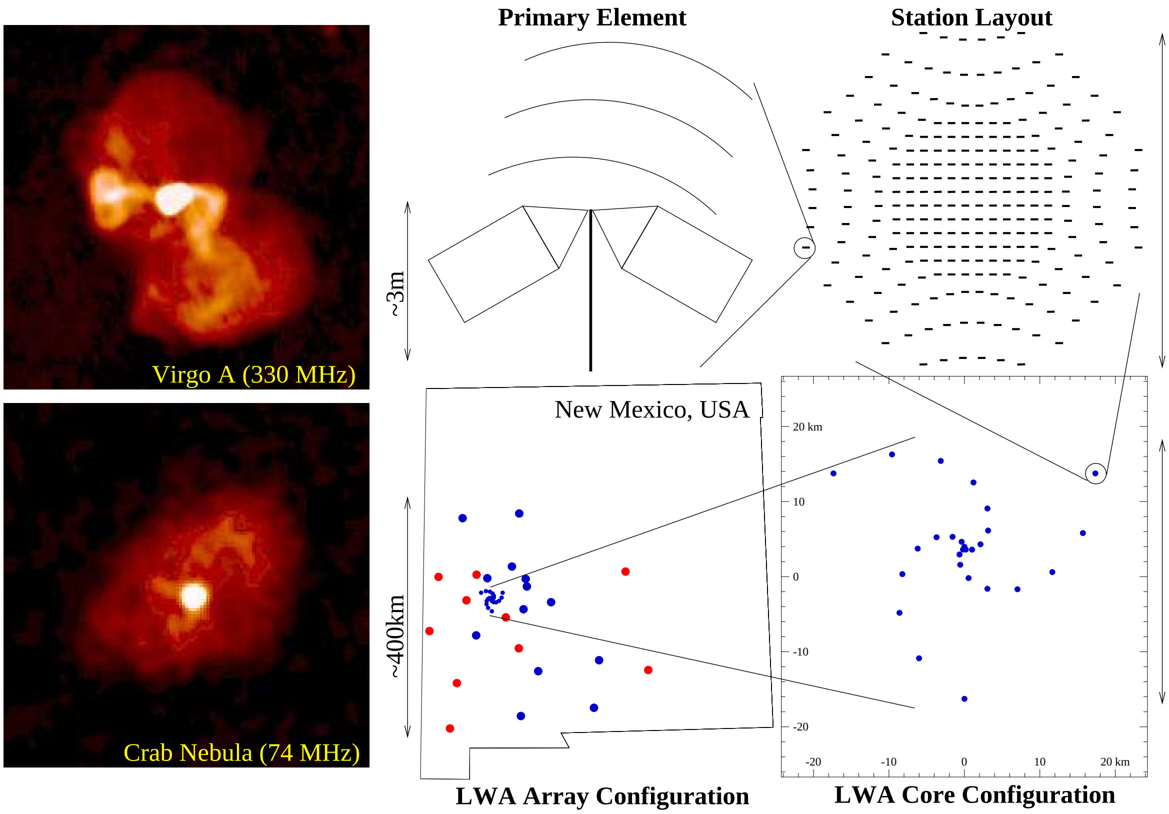
The Long Wavelength Array:
Science Drivers



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Chapter 1

Long Wavelength Science

Numerous scientific projects could be carried out by a sensitive, high–angular-resolution, low-frequency instrument. Unrivaled continuum spectra for studies of shock acceleration and spectral aging in Galactic (supernova remnants) and extragalactic (radio galaxies) sources could be produced. High-redshift radio galaxies and quasars, shocks driven by infalling matter in clusters of galaxies, pulsars in the Milky Way and in external galaxies, and radio bursts from nearby stars and extrasolar planets are examples of steep-spectrum processes that could be detected, and in some cases imaged, in large numbers. A frequency versatile system would be capable of distinguishing between intrinsic (synchrotron self-absorption, source variability) and extrinsic (free-free absorption, scattering) physical processes affecting nonthermal emission at low frequencies. Physical parameters of the ionized interstellar medium (ISM)—cosmic-ray emissivity, emission measure, temperature, pressure, and ionization state—can be constrained from low-frequency observations of H II regions and recombination lines from very high Rydberg state atoms. Below 100 MHz H II regions become opaque, thereby providing "walls" at known distances to allow distance determinations to various foreground objects, in both the Galaxy and external galaxies. Coherent emissions—from the Sun, the Earth and Jupiter, nearby extrasolar planets, and pulsars—occur primarily at low frequencies. Finally, a low frequency system used as a receiver for solar radar transmissions could play an important role in space-weather forecasting.

Chapter 2

Cosmology and Large Scale Structure

After the Universe recombined at $z \approx 1500$, it is generally accepted that it was largely neutral until the epoch of first star formation. Soon after the formation of the first stars, the Universe became re-ionized, probably on a fairly rapid time scale, around $z \sim 10$ (e.g., Gnedin & Ostriker 1997). The large decrease in the abundance of neutral hydrogen accompanying re-ionization should result in a sharp drop in the sky spectrum near 100 MHz.

Detecting this decrement will be challenging as the expected spectral decrement is about 1% of the amplitude of the cosmic background radiation. Nonetheless, it seems possible that the next-generation of long wavelength telescopes might be capable of detecting the signature of re-ionization (Shaver et al. 1999, but see Gnedin & Ostriker 1997).

The LWA would be useful in two respects in a search for the re-ionization signature. First, the inner portions of the array would be sensitive to emission on sufficiently extended angular scales that the array itself could be used to search for the spectral signature. Second, as Shaver et al. (1999) discuss, a crucial aspect of this experiment will be to identify, model, and remove foreground sources of contaminating signal. One such contaminant is discrete radio sources (i.e., radio galaxies and radio-loud quasars). The long baselines of the LWA would assist in the identification of discrete sources in the field(s) of view being observed for the spectral decrement. In both cases—use of the inner portion of the LWA to search for the spectral decrement and exploiting the high angular resolution of the LWA to identify foreground contaminants—the broad band nature of the LWA will be essential. The epoch of re-ionization, and therefore the frequency of the spectral decrement, is uncertain. The broad band nature of the proposed LWA would enable a search for this effect over a finely spaced grid of frequencies, increasing the chances of detecting the effect.

We discuss the identification of fossil galaxies in more detail below (§3.5). Here, we merely note that the successful identification of fossil galaxies would allow their spatial distribution to be studied. In turn, this spatial distribution may provide constraints on the early epochs of large-scale structure formation.

We also discuss the use of radio galaxies as probes of cluster environments in §3.2.2.

Chapter 3

Formation and Evolution of Galaxies

3.1 Cluster Radio Halos and Inter-Galactic Magnetic Fields

A small number of galaxy clusters show radio halos—diffuse, central radio emission not associated with any one galaxy in the cluster. Several models have been proposed to explain the origins of these halos: an injection of relativistic electrons from radio galaxies, *in situ* particle acceleration due to turbulence, or a merger shock wave and secondary production from hadronic interactions of cosmic ray protons with the intracluster medium (for a review see Schlickeiser et al. 1987). While each model has its advantages, none can explain all of the observed features of radio halos.

In particular, most of the models predict a much higher number of cluster halos than observed. The "missing" halos may have escaped detection by virtue of their steep spectra, suggesting that a search at low frequencies would find many more halos. Many models also predict that radio halos are a transient phenomena, suggesting that a pool of relic electrons around a few hundred MeV is expected due to a maximum of the cooling time in this energy range (Sarazin 1999). Indirect evidence for the existence of these relic electrons has been found recently as excess extreme ultraviolet emission from clusters (Hwang 1997; Enßlin & Biermann 1998; Sarazin & Lieu 1998; Bowyer & Berghöfer 1998), emission that may be due to inverse Compton scattering of cosmic background photons (Lieu et al. 1996; Bowyer et al. 1996; Bowyer et al. 1997; Mittaz et al. 1998). If the radio synchrotron emission from electrons with energies of order a few hundred MeV can be detected, the combined radio and EUV information would provide a measurement of the magnetic field strength inside the intracluster medium. A comparison of such an estimate with Faraday rotation measurements for the Coma cluster indicates the existence of highly structured magnetic fields (Enßlin et al. 1999).

Low frequency measurements of polarized background sources are also a sensitive tool for detecting weak magnetic fields outside clusters of galaxies because of the λ^2 dependence of Faraday rotation. The high angular resolution and sensitivity of the LWA may enable it, at the higher end of its frequency range, to measure changes in the Faraday rotation across extended, polarized, background sources. The sensitivity of the LWA will increase the number of background sources that can be used to probe the peripheries of any given cluster and will extend studies of the magnetic fields to the peripheral regions of cluster with good statistics for the first time.

Magnetic fields inside clusters of galaxies are expected from phase transitions occurring after the Big Bang, battery effects at shock waves, injection by radio galaxies and galactic winds, and the action of a turbulent dynamo driven by structure formation flows. An understanding of the properties of large-scale magnetic fields is crucial for an understanding of the origin of the observed cosmic ray events above 10^{18} eV. These particles are believed to be of extragalactic origin so that they had to travel through the large-scale magnetic fields, which should affect their trajectories (Lemoine et al. 1997, Sigl & Lemoine 1998).

3.2 Evolutionary Studies of Radio Galaxies

Radio galaxies are a varied group of objects, ranging from high-luminosity objects extending over megaparsec scales and presumably powered by massive black holes to low-luminosity, relatively small objects powered by star formation. The combination of the high sensitivity and high angular resolution capabilities of the LWA could be brought to bear on a number of outstanding problems in the origin, evolution, and nature of the radio galaxy phenomenon. In this section we survey some of the possible applications of the LWA to the study of radio galaxies.

3.2.1 High-Redshift Radio Galaxies

Roughly 10% of powerful active galaxies produce oppositely directed radio jets which transport a vast supply of energy over distances of upto a few Mpc. These jets feed synchrotron-emitting lobes for as long as 10^8–10^9 yr. With luminosities in excess of 10^{28} W Hz^{-1} sr^{-1}, these objects can be detected at great distances, out to redshifts of 4–5 and beyond. The detection of such high-redshift objects is vital to our understanding of the origin of active galaxies since at the redshifts to which radio galaxies are detected ($z = 4.41$ in the case of 6C*0140+326, Rawlings et al. 1996), for a standard assumed cosmological model, only 1 Gyr has elapsed since the Big Bang. This leaves little time for jet-producing central engines and host galaxies to form.

The high-redshift ($z > 3$) radio galaxies known to date are characterized by very steep spectra ($\alpha < -1$) and small angular sizes ($\lesssim 30''$). These characteristics have been exploited in "filtered" samples of radio galaxies; for example the 6C* sample (Blundell et al. 1998) cross-matched sources from the 151 MHz catalogue of Hales et al. (1993) with a 5 GHz survey to obtain a set of sources with very steep spectra. This procedure led to the detection 6C*0140+326, the currently most distant known radio galaxy ($z = 4.41$, Rawlings et al. 1996). The steep spectrum emission of these high-redshift radio galaxies ultimately limits the utility of a survey at 151 MHz; such a survey selects objects at a redshift z according to their surface brightness at a rest-frame frequency of $(1 + z)\,151$ MHz. For example, in the case of an object at a redshift of 6, the survey would select rest-frame emission near 1 GHz. Above 1 GHz, radio galaxy lobes are subject to synchrotron losses, and in addition their lobes suffer inverse Compton losses off the cosmic background radiation, whose energy density increases as $(1+z)^4$. In order to produce a more complete sample of the high-redshift universe of active galaxies, it is essential to lower the finding-frequency—a task to which the LWA is ideally suited.

The class of low-luminosity radio galaxies with limb-darkened outer structures (Fanaroff-Riley I objects; Fanaroff & Riley 1974), like Virgo A, have typical 1.4 GHz luminosities of 10^{23}–10^{25} W Hz^{-1}. With spectral indices as steep as -0.8, one should be able to detect FR I radio galaxies at 5 mJy flux levels at 74 MHz out to $z = 3$. Moreover, high-z FR I galaxies tend to be diffuse, suggesting that they have much lower magnetic fields than $z = 0$ galaxies. Detection of these sources is particularly interesting because inverse Compton losses scale as $(1 + z)^4$ so that, combined with the weaker magnetic fields, inverse Compton losses should become increasingly important at high z with attendant changes in the properties of these galaxies. Thus, for FR I galaxies, steep spectra and radio morphology might be a much stronger filter for high-z objects than for FR II galaxies. Current telescopes can begin to explore the possibility of detecting high-z FR I radio galaxies, but higher resolution and sensitivity are required to study the effect of inverse Compton losses on these objects.

De Breuck et al. (1998) have also recently discovered a new class of ultra–steep-spectrum, very reddened, dusty quasars. Low-frequency observations would be an efficient means of finding additional objects of this nature.

3.2.2 Radio Galaxies as Cluster Probes

In addition to being interesting in their own right, high-z radio galaxies can also serve as probes of cluster "weather," that is the dynamical state of clusters. If one can image some of these objects at high z, then one can get an indication of the dynamical state of clusters at earlier epochs and thus their evolution.

For instance, the recent analysis of low-frequency images of Virgo A (Owen et al. 1999) indicates that the black holes in cluster cores may compete with the "cooling flow" from the large-scale cluster atmosphere to control the physics in the inner 100 kpc of rich clusters. One might also expect such sources to be longer lived at lower frequencies, and thus show more about the history of such processes through their frequency of occurence, structure, and spectral properties at lower frequencies. Since such sources often have very steep spectra (-2.0 at meter wavelengths), one might hope to detect such sources to very high redshifts and also be able to make a complete census of well-studied clusters nearby.

3.2.3 Emission Mechanisms and Jet Physics

Estimates of the energy budget for radio galaxies are currently hindered by ignorance about the nature and location of the low-energy cutoff of the particle reservoir of the synchrotron-emitting lobes, to the extent that there is over an order of magnitude uncertainty in the values of the jet powers inferred in this way. The secure detection of a *low-frequency* cutoff or turnover would strongly constrain these calculations. The location of the low-energy cutoff is the corner-stone of the recent result of Wardle et al. (1998) that jets must contain a significant population of light pairs ($e^{\pm}$), rather than heavy pairs (p^{+} and e^{-}). This is a key question in astrophysics today, since the composition of the jet material pertains to the nature of the black hole jet-producing mechanism.

Using steep-spectrum radio galaxies and quasars as beacons of the distant universe has many advantages (e.g., radio emission does not suffer obscuration by dust), but basing secure cosmological conclusions on them can only be done if the astrophysical mechanisms by which these objects are governed is understood. Studies of Cygnus A have demonstrated the importance of the lower frequency (151 and 327 MHz) observations in anchoring such studies (Carilli et al. 1991). Previous observations (Myers & Spangler 1985; Alexander & Leahy 1987) have shown a strong spectral-index gradient which steepens from the hotspots back to the core, which may be interpreted as increasing synchrotron losses impacting on the the oldest emitting particles. Such observations confirm the basic models that describe the transport of relativistic particles along collimated jets from the active cores to the hotspots which subsequently feed the radio lobes (Blandford & Rees 1974; Scheuer 1974). However, even a quarter of a century later, the role played by the hotspots in governing the energy supply to the lobes (Blundell et al. 1999) and the lobe-aging processes (Rudnick et al. 1994) have barely begun to be understood. Understanding these are vital, however, for explaining such trends as the strong dependency of spectral index on source luminosity (Heeschen 1960; Laing & Peacock 1980; Blundell et al. 1999). The LWA could observe in the frequency regimes rarely afflicted by synchrotron cooling thereby discriminating between the initial energy distribution supplied by the hotspot and subsequent loss mechanisms as the lobe evolves.

For FR I objects like Virgo A, the very sense of the spectral index gradient is reversed relative to high-luminosity radio galaxies with edge-brightened outer structures (FR II sources), since the energy of the jets is dissipated along their lengths (FR I) instead of at their ends (FR II). Both 74 and 330 MHz observations of Cygnus A (FR II type) and Virgo A have demonstrated these principles (Carilli et al. 1991; Kassim et al. 1993, 1995a). Furthermore, the sharp boundary of the radio halo around Virgo A at 74 MHz (Figure 1) is evidence that this large scale structure is a response to the activity of the black hole-jet system and is a relatively young feature (Owen et al. 1999). The sensitivity and resolution of the LWA would expand such studies beyond the nearest, brightest, and perhaps atypical, sources.

3.2.4 Star Forming Galaxies

Below 10^{23} W Hz^{-1} at 20 cm, the radio sky is dominated by starforming galaxies. At luminosities of 10^{23} W Hz^{-1}, a spiral galaxy has a star formation rate of about 50 $M_{\odot}$ yr^{-1}. At luminosities of 2×10^{21} W Hz^{-1}, the star formation rate is 1 $M_{\odot}$ yr^{-1}, comparable to that in the Galaxy. For centimeter wavelengths, particle lifetimes are similar to the stellar evolution timescales; this similarity probably accounts for the very good correlation between radio and far infrared emission. However, one might expect that at lower frequencies, the particle lifetimes would be longer, and "relics" of previous star formation episodes would be visible. Thus, more galaxies should show star-formation–related emission at lower frequencies. If this is not the case, then there must be an as-yet unknown process responsible for eliminating the particles from the galaxies.

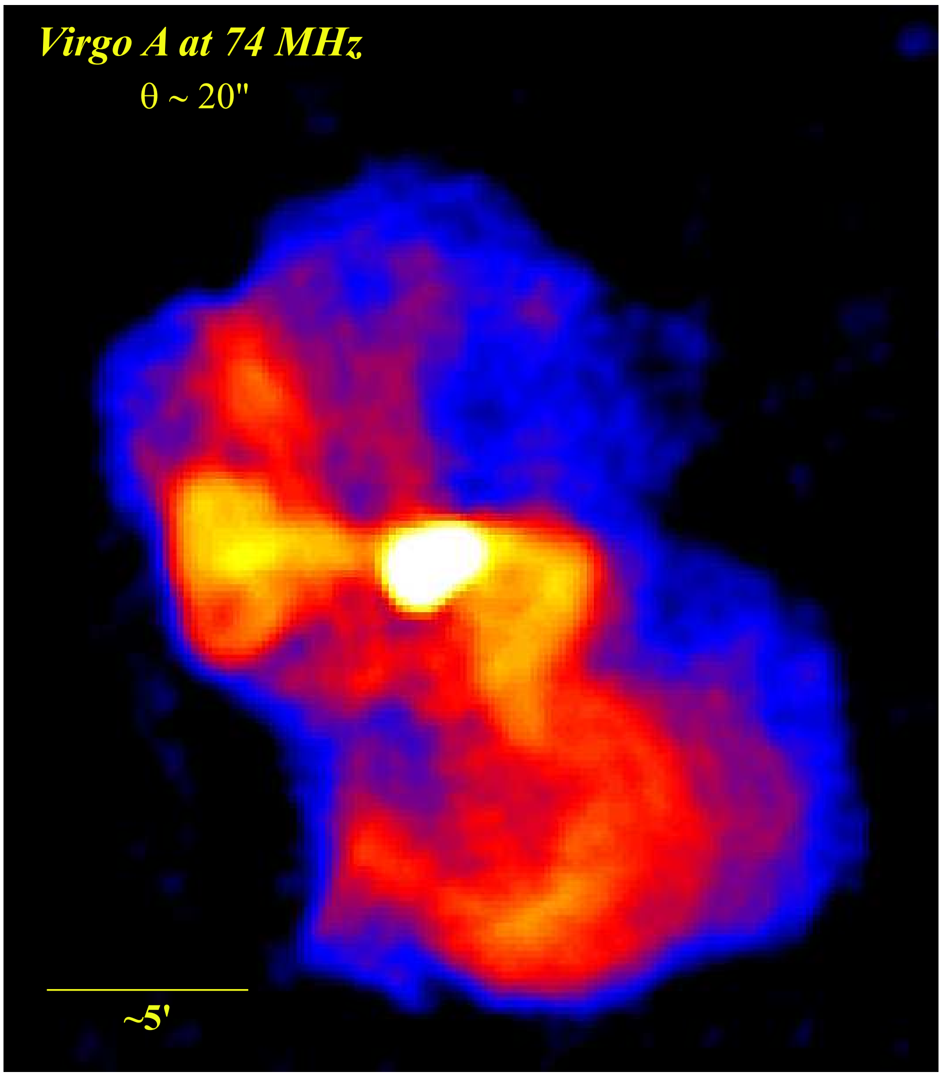

Fig. 1—The active radio galaxy Virgo A at 74 MHz. This figure demonstrates that the large scale radio halo is a response to the activity of the Virgo A black hole-jet system, and, contrary to conventional wisdom, is a relatively young feature (Owen et al. 1999).

Little is known about the spectral properties of these systems at high redshifts. The same arguments that apply to FR I and II radio galaxies apply to these systems. Hence, for typical galactic magnetic fields, one would expect significant spectral steepening and generally steeper spectra for distant star forming galaxies than nearby ones. The sensitivity of the LWA would enable study of these objects at $z \simeq 0.03$, for a Milky Way-like object, with a normal spectral index. Of course, there may be absorption in the neighborhood of these star forming galaxies. The broad-band nature of the LWA would be essential in discriminating between emission from the star-forming process and absorption.

3.3 Galaxy Halo Emission

Synchrotron radio halos have been predicted around all types of individual galaxies and clusters of galaxies but have rarely been reliably detected (Kronberg 1990). In normal spirals the radiation should result from cosmic ray electrons that diffuse or convect out of the disk, and its interpretation bears on questions of cosmic ray origin and transport. In starbursts and Seyferts, high-energy electrons may be funneled away from the nucleus by a disk or be physically transported by jets. In all cases low-frequency observations are critical because they are excellent tracers of large-scale structure and because the physics underlying the radiation losses suffered by the transported electrons is revealed through the sense of the spectral-index gradients, as is the case of the radio galaxies. Such measurements could be crucial to the interpretation of X-ray halos since, for example, if the X-ray halo recently detected around the edge-on spiral NGC3628 is produced by synchrotron emission, then a steep-spectrum radio halo should also be present.

It is usually difficult to distinguish halo emission from disk emission, and the emission from the galactic disks probably confused most early reports of halo emission. Observations of edge-on galaxies are of particular relevance since, in these cases, disk and halo radiation can be clearly distinguished. The halo emission that has been found in some edge-on galaxies has been attributed to cosmic-ray particles that have been convected out of the disk by gas ejected in superbubbles generated by vigorous starburst activity (Werner 1988). This topic is of great importance in cosmic-ray physics since it pertains to the storage and propagation of cosmic rays in the environment of galaxies, and it also contributes to our understanding of disk-halo interactions in galaxies. The radio spectra of the halos are often steeper than those of the disks, as would be expected for old electrons spiraling in weak magnetic fields. Although low frequencies are the most appropriate for the study of halo emission, sufficient angular resolution and sensitivity have not been available to conduct such work. A major advantage of the lower frequency observations is that they are potentially powerful discriminators of convective and diffusive halo models. Most models of convection-dominated halos predict a low-frequency flattening which should be easily visible (Lerche & Schlickeiser 1982a, 1982b).

3.4 Emission and Absorption Mechanisms in Galaxies

A variety of absorption processes is expected to occur in and around radio galaxies at low frequencies. These include synchrotron self-absorption, Razin-Tsytovich suppression, turnovers caused by low-energy cutoffs in electron energies, and absorption by thermal gas. All of these mechanisms exhibit different spectral signatures, emphasizing the importance of the broad-band LWA. While evidence for the existence of these processes, based on turnovers in integrated low-frequency spectra, has existed for some time, poor angular resolution has prevented essentially all but the simplest conclusions. For instance, 151 MHz observations support the conclusion that the flattening of the hot spot spectra in Cygnus A is due to a low-energy cutoff in the radiating electrons and not thermal or synchrotron absorption (Carilli et al. 1991). However, the poor angular resolution of the present 74 MHz VLA prevents a definitive test of this conclusion (Kassim et al. 1995a). The LWA would measure the entire low-frequency hotspot spectrum which is vital for understanding how the hotspot governs the energy distribution to the lobe.

In normal galaxies, such as M82, Wills et al. (1997) detected an unexpected free-free absorption of SNRs by giant H II regions at relatively higher frequencies (151 and 408 MHz) than those seen toward Galactic SNRs (Kassim 1989). Such measurements place constraints on the radial location of the discrete non-thermal sources relative to the ionized component of the host galaxy ISM. VLA and Westerbork observations at 330 MHz and MERLIN observations at 151 and 408 MHz can search for such effects, but lower frequency observations are more sensitive to absorption. The arc-second resolution of the LWA is needed for such studies. On larger scales the integrated spectra of many normal spiral galaxies appear to flatten near 100 MHz. This flattening maybe due to free-free absorption by cool ISM gas (Israel & Mahoney 1990; Hummel 1991; Israel et al. 1992) and could be explored far better with the LWA.

3.5 Fossil Galaxies

Synchrotron aging of a relativistic electron population preferentially depletes the high-energy electrons first. Low-energy electrons, which radiate at low radio frequencies, have the longest lifetimes. This has prompted speculation about populations of electrons whose radiation lifetimes exceed the Hubble age and has led to the suggestion of the existence of extremely steep-spectrum "fossil galaxies." Estimates of the energy release during the first epochs of radio galaxy activity suggest that these fossil galaxies should be relatively common in the intergalactic medium (Enßlin et al. 1998b). If such fossil galaxies do exist, the proposed LWA would be ideal for detecting them. In addition to information about the oldest electron populations, such observations could provide valuable information about intergalactic or primordial magnetic fields.

Enßlin et al. (1998a) have recently suggested that so-called "cluster radio relics" in the vicinity of clusters of galaxies are in fact such fossil galaxies with a shock-accelerated relativistic electron population. The necessary shock waves would be megaparsecs in scale and could be due either to steady accretion of matter onto the cluster of galaxies or due to a merger event with another cluster (e.g., Abell 2256). Recently observed substructures in X-ray temperature maps support the existence of extended strong shock waves at the locations of several of the known cluster radio relics (Abell 85, Markevitch et al. 1998a; Abell 1367, Donelly et al. 1998; Abell 2256, Roettiger et al. 1995; Abell 3367, Markevitch et al. 1998b). Figure 2 shows an example of these proposed shocks around the X-ray cluster Abell 3667; both (thermal) X-ray emission from the cluster core and 843 MHz radio emission from the shock-accelerated electron population in the presumed infalling matter shocks are visible.

Re-activated fossil galaxies are a powerful tool to investigate properties of the infalling matter onto clusters of galaxies and are a test ground for large-scale structure formation. They are steep-spectrum sources, especially if the shock is weak, so that low-frequency observations are required in order to detect more of them. An observation of a re-activated fossil galaxy at the weaker accretion shock at the boundary of a sheet or filament of galaxies would be very challenging for cosmology

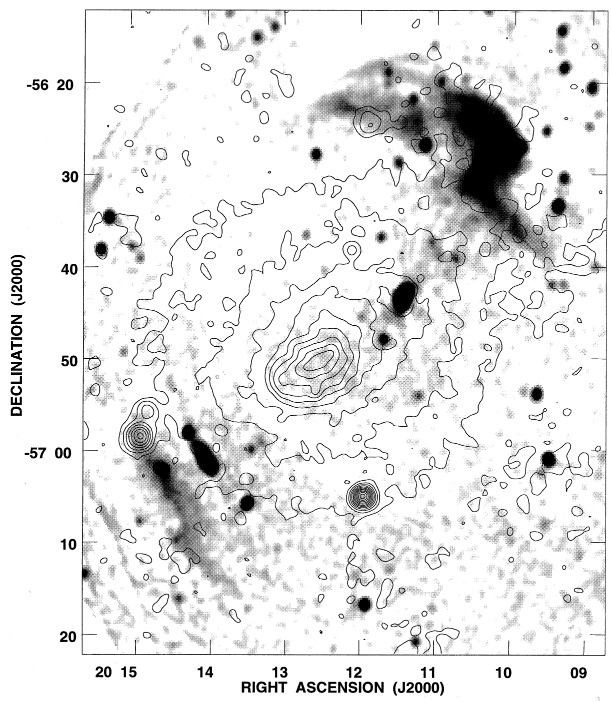

Fig. 2—Steep spectrum halo emission from Abell cluster 3667. A contour representation of the ROSAT PSPC image (0.1–2.4 keV) of Abell 3667, overlaid on a grey-scale of a wide-field 843 MHz MOST image (Röttgering et al. 1997). The steep spectrum radio emission may be the shocks formed between infalling matter and the cluster core.

Fig. 3—Components of the ISM

Phase	f	n (cm^{-3})	kT (eV)	nkT (eV cm^{-3})
Molecular Clouds	10^{-3}	> 100	$< 10^{-2}$	-
Cold Neutral Medium	0.025	40	$\approx 10^{-2}$	≈ 0.4
Warm Neutral Medium	≈ 0.5	≈ 0.5	≈ 1	≈ 0.5
Warm Ionized Medium	≈ 0.25	≈ 0.2	≈ 1	≈ 0.2
Hot Ionized Medium	≈ 0.2	$\approx 3 \times 10^{-3}$	$\approx 10^2$	≈ 0.3
Cosmic Rays	≈ 1	$\approx 10^{-9}$	$\approx 10^9$	≈ 1

and only expected to be successful at very low frequencies.

Chapter 4

Interstellar Processes

4.1 The Origin of Cosmic Rays

The holy grail of cosmic-ray physics is the answer to the question of their origin. This problem remains unsolved some 87 years after the discovery of cosmic rays by Hess (1912). Viable cosmic-ray origin theories did not even appear for some 65 years. Since then, our understanding of cosmic-ray properties has grown enormously. We now know that cosmic rays are mainly atomic nuclei and electrons that have been accelerated to energies greater than their rest mass energies. They follow a nonthermal power-law distribution with a differential energy index of approximately 2.5. Their energy density in space is approximately 1 eV cm^{-3} which translates into a number density of 10^{-9} cm^{-3}. Thus, cosmic rays can be collectively characterized as a *collisionless, nonthermal gas*. It is instructive to compare the properties of this nonthermal gas with that of the various components of the ISM. Table 3 shows this comparison.

Column 1 lists the various phases of the ISM. Approximate filling factors are shown in column 2. The number density is shown in column 3. The kinetic energy per particle from each phase is shown in column 4 in electron volts. Column 5 lists the energy density of each phase.

Cosmic rays are energetically important, *containing at least as much energy as the other phases of the ISM.* They therefore play an important role in the evolution of the ISM and should be

Fig. 4—Global Measurements of Cosmic Rays

Components	Tracer	Related ISM Component	CR Energy Range	Quantity Measured
Electrons	Radio Synchrotron	$\mathbf{B}$	0.2–10 GeV	$\int n_{\rm CR} B^{1.8}\, dr$
Electrons	Radio Bremsstrahlung	Thermal ISM	100–300 MeV	$\int n_{\rm H} n_{\rm CR}\, dr$
Electrons	γ-ray Inverse Compton	Photons	< 100 MeV	$\int n_{*} n_{\rm CR}\, dr$
Protons	γ-ray π^0 Decay	Thermal ISM	0.3–10 GeV	$\int n_{\rm H} n_{\rm CR}\, dr$

considered as a legitimate phase of the ISM worthy of detailed study.

4.1.1 Measuring Galactic Cosmic Rays

Being charged particles, cosmic rays are easily deflected by Galactic, interplanetary, and geophysical magnetic fields. It is therefore generally impossible to deduce the origin and complete spectrum of the cosmic-ray particles from direct measurements. There is, however, a wide array of measurement tools available for studying Galactic cosmic rays indirectly. Table 4 summarizes the most commonly used tracers of the global distribution of cosmic rays.

Column 1 lists the cosmic-ray component that is probed. The mechanism by which the component is detected is shown in column 2. Column 3 shows the component of the ISM with which the mechanism is associated. The range of energies of the cosmic ray particles contributing to the observed emission is shown in column 4. The quantity actually represented by the observed emission is shown in the last column.

It is clear that multiple tools exist for tracing cosmic rays in the Galaxy. However, it is also obvious that all global tracers of cosmic rays are tied to other components of the ISM and that no global tracer measures the cosmic rays directly. Furthermore, examination of Table 4 shows that there is little overlap in electron energies among the three electron tracers. In fact, there is *no* overlap between cm-wave radio emission and the two $\gamma-$ray tracers. This absence of overlap is illustrated in Figure 5 (from Longair 1990).

However, at the lower radio frequencies ($\approx$ 10 MHz–30 MHz), relativistic electrons with $E \approx$ 200–300 MeV are traced under typical interstellar conditions. This is a region of the energy spectrum that is not possible to study through direct detections because of solar modulation. These same electrons also radiate relativistic bremsstrahlung at the lower γ-ray photon energies (Table 4). Consequently the equations in rows 1 and 2 of Table 4 can be combined (in conjunction with the well established data base of Galactic H I emission) to determine uniquely the distribution of cosmic-ray electrons in the Galaxy, *separately from the magnetic field distribution*, a key problem in understanding the origin of cosmic rays.

Though low-frequency radio astronomy paved the way for opening up the field of cosmic-ray astrophysics, it has had a relatively minor role to play since the pioneering efforts of Jansky (1935) and Reber (1940). The major reason for the irrelevancy of low-frequency radio astronomy to cosmic-ray studies has been the limitations imposed by the Earth's ionosphere. However, with advances being made in phase-calibration and phase-transfer techniques (e.g., Kassim et al. 1993), there

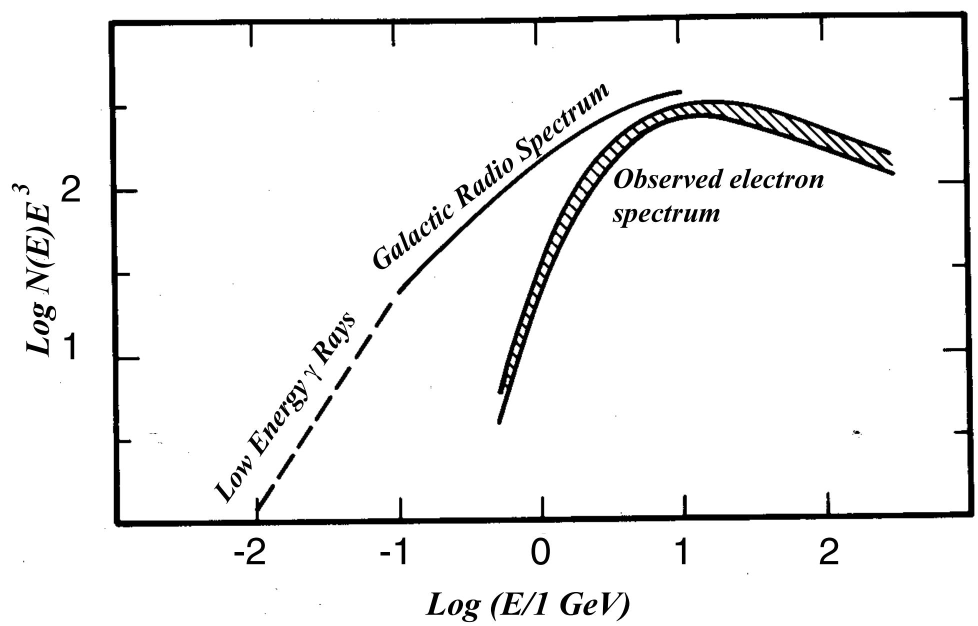

Fig. 5—The spectrum of relativistic electrons in the local ISM (from Longair 1990). The directly observed electron energy spectrum is shown in the hatched area. Modulation by the solar wind prevents direct measurement of the intrinsic spectrum below roughly 10 GeV. The electron spectrum derived from the spectra of the Galactic low frequency radio emission (solid line) and low energy gamma ray emission (dashed line) are also shown. There is no overlap between the radio observations and the $\gamma-$ray observations.

are no longer any technological obstacles to building an array capable of tackling the cosmic-ray problem.

The key questions that relate to a full understanding of Galactic cosmic rays are the following.

- How are cosmic rays distributed in space?
- How are cosmic rays accelerated?
- What are the energetics of Galactic cosmic rays?

Low-frequency radio astronomy has the potential to provide answers to each of the above questions, as detailed below.

4.1.2 Distribution of Cosmic Rays in the Galaxy

All sky surveys at (cm-wavelength) radio and $\gamma-$ray wavelengths show similar emission morphologies. Haslam et al. (1981) compared the (latitude-averaged) longitudinal distribution of (COS-B) $\gamma-$ray and radio emission. Although the profiles differ substantially in directions of specific sources such as Cas A, Vela and the Galactic center, the overall distributions, reflecting the diffuse emission, are remarkably similar even showing enhancements along the spiral arm tangents. The $\gamma-$ray data measure the integral product of cosmic rays and thermal gas along a given line of sight (Table 4, column 5) while the radio data represent the same for cosmic-ray electrons and magnetic fields. Thus, the above similarities could represent the cosmic ray distribution but they could equally well represent a correlation of gas and magnetic fields. A further complicating factor is that cm-wavelength radio emission traces GeV electrons while the γ-ray (relativistic bremsstrahlung) emission traces sub-GeV electrons.

As discussed earlier, low-frequency radio emission from the ISM traces the same sub-GeV electrons (for frequencies < 100 MHz). Consequently, a comparison of low-frequency radio emission with mid-energy γ-ray emission, in conjunction with H I emission, should yield a much improved estimate of the cosmic-ray distribution. A favorable consequence of estimating the cosmic ray distribution is that the line-of-sight–averaged magnetic field can then be estimated by inverting the synchrotron equation (Table 4, row 1).

At radio frequencies of 10–100 MHz, H II regions become optically thick. Observations of low-frequency synchrotron emission in the direction of such remnants offers a unique opportunity to measure synchrotron emissivity along columns whose lengths are given by the distances to the H II regions. It may therefore be possible to build a 3-dimensional model of the electron distribution in the Galaxy. Such a model would offer new insights into the geometry of the Galactic cosmic-ray disk and/or possible halo.

4.1.3 The Acceleration of Cosmic Rays

The current paradigm holds that high-energy phenomena, related to supernovae and/or active galactic nuclei (AGNs), are the sources of cosmic rays. However, no direct connection between the particles that we observe locally and any identified cosmic sources has been made, leaving their origin uncertain.

As early as the 1930's, Zwicky (1939) suggested that supernovae were somehow responsible for the acceleration of cosmic rays. This idea was proposed even before the connection between cosmic rays and galactic radio emission was made. Although the supernova idea was much closer to the currently accepted view of cosmic-ray acceleration, it was recognized quite early that strong adiabatic losses prevented significant particle acceleration during the supernova expansion. Instead, it was proposed that it is the interaction of the supernova remnants with the ISM that leads to the acceleration of cosmic rays. The idea was first developed by Bell (1978a, b) using the concept of first-order Fermi acceleration. Subsequent work has evolved this idea into what is currently known as diffusive shock acceleration (DSA). DSA is fully reviewed by Ellison et al. (1994) and, to a lesser extent but more recently, by Jones et al. (1998).

The DSA mechanism in conjunction with SNRs appears to be able to account for the vast majority of cosmic rays (those with energies $\approx 10^9$–10^{15} eV). However, the classic problem of the injection mechanism (the ability to accelerate seed particles from the thermal pool) remains unsolved (see, Ellison et al. 1994; Jones et al. 1998). A separate mechanism is required to energize particles to sub-GeV energies in order to inject the necessary seed particles into the DSA environment. Low-frequency radio astronomy is ideally suited for addressing this problem. In supernova remnants (SNRs), where magnetic fields range from 10 μG to 1 mG, the synchrotron-emitting electrons have significantly lower energies at a given critical frequency. At 10–30 MHz, the electrons span the energy range 15–750 MeV, exactly the range needed to study the nature of the injection mechanism. The shape of the electron spectrum and the spatial correlation of hot-spots with shock features, at these energies, would provide robust constraints on the mechanism that accelerates seed particles in SNRs.

4.1.4 Energetics of Cosmic Rays

An important constraint on cosmic-ray origin is the energy density of cosmic rays in the Galaxy. Knowing the distribution of cosmic-ray energy densities in the ISM makes it possible to estimate the energy budget of Galactic cosmic rays. Any plausible sources of cosmic rays must be consistent with such an energy budget.

Direct measurements of cosmic ray fluxes at the top of the Earth's atmosphere suggest that the energy density of cosmic rays is about 0.5 eV cm^{-3}. However, this number is a lower limit because the flux is reduced by the outflowing solar wind which strongly modulates the cosmic-ray flux, particularly below about 1 GeV. Pioneer and Voyager spacecraft have been making *in situ* measurements of cosmic-ray fluxes as they proceed out of the solar system (e.g., Webber 1990). Their measurements indicate that the energy density of cosmic rays is slowly increasing with distance from the Sun. At 70 AU, the value is about 1.5 eV cm^{-3}. The spacecraft have not yet reached the heliospheric boundary. When they do, they will be making measurements in the true ISM, local to the Sun.

Unfortunately, these direct measurements are very local and do not tell us about the energy densities of cosmic rays in other regions of the Galaxy. The energy densities have to be inferred from the synchrotron emission of the relativistic electrons. Interpretation of the synchrotron all-sky maps by Beuermann et al. (1985) suggests that the energy density of cosmic rays increases from about 1 eV cm^{-3} at the solar circle to about 6 eV cm^{-3} at 4 kpc from the Galactic center. The interpretation of $\gamma-$ray data suggests similar numbers (e.g., Strong et al. 1996). However, these studies are severely hampered by the projection of emission along the line-of-sight. Low-frequency radio astronomy offers the advantage of being able to measure actual path lengths, thereby greatly improving estimates of energy densities in the Galaxy. This is achieved by spatially resolving optically thick H II regions (very common at low frequencies), of known distance, against which the distributed synchrotron emissivity can be accurately determined (Kassim 1990). The power of this approach is the availability of relatively well-determined path lengths to the H II regions, allowing the true three-dimensional space distribution of cosmic-ray–induced synchrotron emissivities to be determined. A comparison of the local synchrotron emissivity with the known local energy density of cosmic rays would form the calibration needed to convert synchrotron emissivities to cosmic-ray energy densities.

Once the energy budget of cosmic rays is determined, then it is possible to critically compare the energetics of proposed cosmic-ray sources. For example, the supernova rate for our Galaxy is estimated to be about 1 per 30 yr. If a supernova produces 10^{51} ergs of kinetic energy, the average energy input rate is roughly 10^{42} erg s^{-1}. This number is comparable to the energy rate needed to maintain the Galactic cosmic rays (making specific assumptions about the poorly known energy density of cosmic rays in other parts of the Galaxy, e.g., Jones et al. 1998).

The above approach can be carried to external galaxies (which by virtue of their better perspectives minimize the "forest for the trees" problem associated with the Galaxy). Studies of SNRs in external galaxies, at cm wavelengths, have led to calculations of energy budgets showing that SNRs may in fact provide the needed energy (Duric et al. 1993; Duric et al. 1995; Gordon et al. 1998; Lacey 1998). However, these studies could be improved greatly at lower frequencies. The above studies have found strong spatial correlations of SNRs with H II regions. Consequently, the thermal emission from the H II regions strongly contaminates the radio emission from the SNRs. The LWA, capable of $1''$ imaging and 1-mJy sensitivity at frequencies below 100 MHz, will allow the detection of SNRs even in the most confused regions of galaxies. The improved statistics would prove invaluable in gauging the role of SNRs in regulating the cosmic-ray production in external galaxies.

4.2 Supernova Remnants

Supernova remnants, extended nonthermal emitting sources that are the principal sources of energy input into the ISM, are natural targets for study at low frequencies. Moreover, their often large angular sizes are well matched to the large fields of view normally available at low frequencies. An excellent example is provided by Figure 6, a wide-field image of the Galactic center made with the VLA at 330 MHz (Kassim et al. 1998). This image was used to discover the second closest known SNR to the Galactic center (Kassim & Frail 1996), and with this image a variety of other, previously unknown, nonthermal sources have been discovered in this extremely complex region. Low-frequency studies of SNRs at high angular resolution and sensitivity should prove equally adept at finding new SNRs.

High-resolution, low-frequency radio images will also serve to anchor spectral index studies of SNRs whose spatially resolved continuum spectra uniquely constrain the energy distributions of relativistic electrons. The key is to relate measured source spectral variations to dynamical structures, since models of particle acceleration in SNRs, either by shocks or by second-order Fermi (stochastic) acceleration in interior turbulence, predict structure in the particle distributions. Measured variations must be related to acceleration processes or the injection spectrum of the seed particles. Variations in older SNRs can also be related to compression of cosmic-ray gas and interstellar magnetic fields. Previous studies have had far too poor angular resolution at the lowest frequencies to explore such issues in detail, if at all.

Centimeter-wavelength studies of Cas A (Anderson & Rudnick 1996) have suggested that the spectrum of the emitting regions may be determined not only by current acceleration processes but also by the history of particle acceleration in the environment through which the particles have moved. Observations with the 74 and 330 MHz VLA systems have recently confirmed this

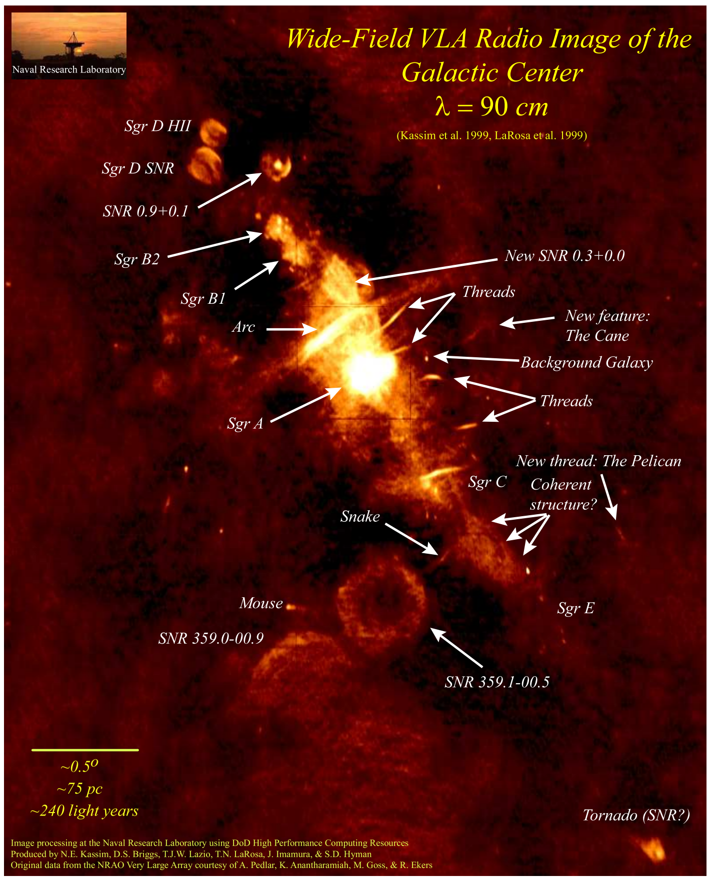

Fig. 6—A 330 MHz image of the Galactic center obtained with the VLA. This image covers $4^\circ \times 4^\circ$ at a resolution of $48'' \times 48''$. The rms noise level (excluding the bright sources on the Galactic ridge) is 5.9 mJy beam^{-1}.

surprising conclusion. Perhaps even more exciting has been the unique absorption measurements provided by the 74 MHz observations which reveal evidence for unshocked ejecta *within* Cas A, as predicted by theory (Kassim et al. 1995b). This measurement raises the prospect that many young supernova remnants may harbor cool thermal cores, that the low-frequency measurements can uniquely detect. The 74 MHz VLA system has also successfully detected thermal absorption from thermal filaments within the Crab nebula (Bietenholz et al. 1997). The detection of thermal absorption from within the first two SNRs observed with the new VLA system suggests that these effects may be common at low frequencies.

In addition, useful information can be gained simply from the integrated low-frequency spectra of SNRs. Predictions from Fermi-acceleration theory imply concave integrated spectra (i.e., hardening at higher frequencies) such as have been claimed in the case of the Tycho and Kepler's SNRs (Reynolds & Ellison 1992). But large error bars on the lowest-frequency measurements hamper these conclusions and restrict their extension to many more sources. Also, the Clark Lake 30 MHz studies of SNRs (Kassim 1989) were able to confirm and extend the original Culgoora 80 MHz SNR studies (Dulk & Slee 1975) which showed evidence of patchy foreground absorption by thermal gas in the ISM. More accurate, higher resolution measurements can extend such studies to many more objects and confirm whether the line-of-sight thermal absorption is indeed related to envelopes of normal H II regions as is currently speculated.

Sensitive low-frequency observations should lead to the discovery of older, low–surface-brightness SNRs which are known to be missing from catalogs due to severe selection effects (Green 1991). Discovery of such older SNRs, at the last stage of evolution before blending into the ISM, are potentially of great importance in discovering new pulsar-SNR associations and drawing links to unidentified γ-ray sources. Presently only the youngest pulsars can be associated with SNRs since remnants older than about 10^5 yr have surface brightnesses too low for detection by current instruments.

The sensitivity and angular resolution of the LWA would extend these SNR studies to nearby external galaxies, increasing greatly the data base. Recent statistical studies (e.g., birthrates, distribution, energetics) of complete, co-distant samples of SNRs in nearby galaxies are proving extremely useful for exploring problems in stellar evolution, ISM structure, and for increasing sample sizes of poorly understood SNR sub-classes (Duric et al. 1995; Jones et al. 1998). Sensitive, high-resolution, low-frequency observations are required to complement existing higher frequency data by anchoring derived spectra, probing for ISM absorption effects (Wills et al. 1997), and to find new remnants.

4.3 H II Regions

Observations at 330 MHz have demonstrated that measurements of optically thick H II regions can constrain source electron temperatures, emission measures, and filling factors (Kassim et al. 1989; Subrahmanyan & Goss 1996). At lower frequencies these regions appear as cooler regions against a much hotter Galactic background, allowing kinematic distance ambiguities to be resolved and the superposition of thermal and nonthermal sources to be separated along complex lines of sight through the Galaxy.

A classic example is the 330 MHz VLA observation which revealed the thermal Galactic center source Sgr A West in absorption against the nonthermal-emitting Sgr A East supernova remnant (Pedlar et al. 1989), constraining the superposition of these sources along the most confused Galactic line of sight known. Observations with the 74 MHz VLA system promise to expand significantly the number of lines of sight on which this technique can be utilized, though a broad-band system which can follow the onset of absorption at high angular resolution and as a function of frequency would make such studies far more powerful.

Kinematic-distance ambiguities resulting from radio-recombination-line measurements can be resolved using the detection, or non-detection, of H II regions in absorption below 100 MHz (Kassim 1990). This is because foreground ("near") H II regions would be much more prominent absorption features on low-frequency LWA maps than distant ("far") ones.

4.4 Interstellar Propagation Effects

All Galactic and extragalactic radio sources are observed after their radiation has propagated through the Galactic plasma. Variations in the plasma density produce refractive index fluctuations, scaling as ν^{-2}, which in turn scatter the radiation. The magnitude of radio-wave scattering from the interstellar plasma is strongly direction dependent, but the effects can remain significant at frequencies of 10 GHz (Walker 1998) or higher (toward the Galactic center, Lazio & Cordes 1998). The density (refractive index) microstructure responsible for interstellar scattering occurs on scales of order 1 AU. The density fluctuations, in turn, are thought to arise from velocity and/or magnetic field fluctuations. In addition to their corrupting effects, interstellar propagation effects are a powerful sub-parsec probe of the interstellar plasma, can provide a tracer of energy input into the ISM, and may be linked to cosmic ray propagation (§4.1).

Low-frequency observations of compact sources provide a powerful diagnostic of propagation effects from the ISM. The scatter-broadened angular diameter of a compact nonthermal source scales as λ^2, while the resolution of a telescope and the minimum apparent size constrained by synchrotron self-absorption both scale as λ. Thus, interstellar scattering studies are optimized with high-resolution, low-frequency observations.

The LWA would prove useful for interstellar scattering studies in two respects. First, it would simply increase the number of lines of sight on which scattering observations could be conducted. The most recent compilation of scattering observations contained 223 sources (Taylor & Cordes 1993). The LWA could increase the number of known pulsars by a large amount (§6.1). Scattering observations can also be exploited to select sources at various distances. For instance, at low frequencies pulsars in and beyond the Galactic center would be resolved out by the LWA (Cordes & Lazio 1997), but pulsars in the inner Galaxy between us and the Galactic center (e.g., in the molecular ring) will still be detectable. The vast majority of scattering studies, however, have been conducted using compact extragalactic sources viewed through regions of intense scattering (e.g., Cygnus, Spangler & Cordes 1998; the Galactic center, Frail et al. 1994; Yusef-Zadeh et al. 1994), where the scattering effects can be detected at frequencies near 1 GHz on baselines of length 50–5000 km. Figure 7 illustrates this bias toward regions of intense scattering. Because of the λ^2 scattering dependence *vs.* the λ synchrotron–self-absorption–size dependence, the LWA would enable studies of the density and field microstructure in less intense scattering regions, such as those near the Sun.

Second, the LWA could be expected to contribute to a better understanding of the generation of the (turbulent?) density fluctuations, their distribution in the Galaxy, as well as the detection of some novel effects that probably cannot be detected at higher frequencies.

Density Fluctuation Genesis Current shock-acceleration theories (Ellison et al. 1994), relevant to the origin of cosmic rays, also suggest that upstream of a SNR should be an ideal site for the

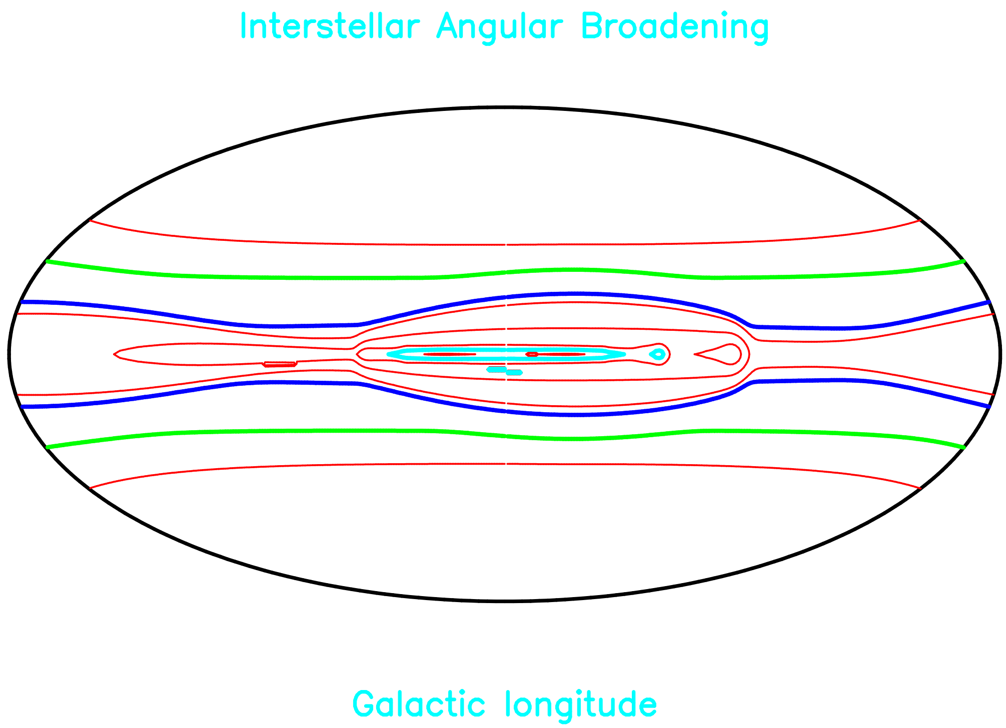

Fig. 7—The Galactic distribution of interstellar scattering. The thin red lines are contours of constant angular broadening diameter as calculated from the Taylor-Cordes model (Taylor & Cordes 1993) at 1 GHz. The Galactic center is at the center of the figure and Galactic longitude increases to the left. The heavy cyan line delineates the regions of scattering accessible to an interferometer with 30 km baselines operating at 74 MHz (e.g., VLA). The heavy blue line delineates the regions of scattering accessible to an interferometer with 8000 km baselines operating at 330 MHz (e.g., VLBA). The heavy green line delineates the regions of scattering accessible to an interferometer with 500 km baselines operating at 20 MHz (e.g., LWA). This model does not account for a few lines of intense scattering, so localized regions of intense scattering may exist outside of these nominal limits that could be studied by these instruments.

generation of the density fluctuations responsible for interstellar scattering. High-frequency searches for the signatures of such upstream turbulence have a mixed record (Spangler et al. 1986). The λ^2 dependence of interstellar scattering would allow much more stringent tests to be applied.

Galactic z-Distribution of Scattering Ionized gas is found several kiloparsecs above the Galactic plane (the "Reynolds layer"). The scale height of the density fluctuations responsible for interstellar scattering is about 1 kpc, inferred from observations of high-latitude pulsars (particularly those in globular clusters) and low-frequency interplanetary scintillation measurements. The agents presumed to be responsible for generating density fluctuations—SNRs and H II regions—have a much smaller scale height (~ 0.1 kpc). As Figure 7 illustrates, the LWA could probe to higher latitudes than existing instruments and would provide additional information about the vertical distribution of the scattering material and clues about any other agents responsible for generating the density fluctuations. Particularly valuable would be deviations from the smooth distribution of scattering material predicted by current models (Taylor & Cordes 1993).

Three-Dimensional Distribution of Scattering The magnitude of scattering observables, e.g., angular broadening, depends not only upon the total rms electron density fluctuations toward a source, but also upon their distribution along the line of sight. For instance, angular broadening is more pronounced the closer the scattering medium is to the observer. Thus a comparison of the amount of angular broadening along similar lines of sight to a Galactic and extragalactic source can reveal the *radial* distribution of the scattering medium (Moran et al. 1990; Lazio & Cordes 1998). Furthermore, different scattering observables have different radial dependences. For instance, consider a pulsar at a distance D and a localized region of scattering at a distance x with $0 \leq x \leq D$ and $s \equiv x/D$. Then the magnitude of pulse broadening depends upon the distribution of scattering weighted by $s(1-s)$ while angular broadening is weighted by s^2(Cordes & Rickett 1998). Thus, a comparison of scattering observables toward the same object can also reveal the *radial* distribution of scattering toward that object. High-frequency observations have shown, perhaps not surprisingly, that scattering toward the Crab pulsar is dominated by the Crab Nebula (Gwinn et al. 1993). The LWA could extend such studies to a much larger number of pulsars, allowing the local *three-dimensional* distribution of scattering to be mapped.

Spatially Limited Scattering The density fluctuations responsible for interstellar scattering have a spatial spectrum. The largest scale on which these density fluctuations occur is about 1 pc near the Sun and may be of the order of 0.01 pc in regions of intense scattering; this scale is presumably related to the injection of energy into the ISM that produces the density fluctuations. At low frequencies the angular extent of the scattering region may be less than the nominal scatter-broadened angular diameter of a background source. If so, the shape of the scatter-broadened image may be affected by the fact that the scattering is occurring only in a limited volume (Cordes 1990). The orientation and distortion of the image would then provide information about the volume in which the scattering was occurring.

4.5 Carbon Recombination Lines

As interstellar carbon ions recombine into very high Rydberg states (up to $n = 768$), absorption lines below 150 MHz are generated. The carbon atoms in these high states are very sensitive to the interstellar environment and permit excellent measurements of density, temperature, and ionization levels to be carried out (Payne et al. 1994). A number of Galactic regions that produce these lines have been found, including a large region that stretches 40° along the Galactic plane in the central region of the Galaxy (Erickson et al. 1995). Until now, all observations of these lines have been made with filled apertures with extremely low angular resolutions. The very central portion of the LWA should have sufficient surface-brightness sensitivity for detection of these lines and would provide much needed angular resolution to map their distribution. The sensitivity of the LWA would be sufficient not only to increase the number of such regions studied in the Galaxy, but also would allow these studies to be extended to external galaxies.

Chapter 5

Solar System Science

5.1 Solar Radar

There is at present great interest in developing a means of detecting and predicting the arrival times of *Earthward-directed* coronal mass ejections (CMEs), the main cause of increasingly costly geomagnetic storms. Until now the best way of studying CMEs has been from space, which is expensive and often unreliable. Furthermore, as Figure 8 illustrates, space-based coronographs are not well suited for studying Earthward-bound CMEs. A revolutionary ground-based technique of detecting and tracking CMEs with long-wavelength solar radar is now being considered, and the LWA would be an ideal imaging receiver for such experiments.

The El Campo radar, built by the Lincoln Laboratory, detected 38 MHz radar echoes from the Sun for a period of 9 years in the 1960's (James 1968, 1970). Huge, rapidly-moving "targets" were occasionally observed but this was before the space-borne coronagraph discovery of coronal mass ejections (CMEs; Gosling et al. 1974), and the physical nature of these "targets" was a mystery. It is now thought that CMEs were being observed.

The reliable detection and monitoring of CMEs is of great practical importance. CMEs that impact the Earth's magnetosphere can result in hundreds of millions of dollars in damage to spacecraft, communication, and electrical power systems. A low-frequency transmitter coupled with a high–angular-resolution receiving array would form an extremely cost-effective system to detect and track CMEs.

Rodriguez (1996) has summarized the potential of 10–80 MHz radar systems for detecting CMEs; Figure 9 illustrates the basic principle. The Doppler shift introduced by different parts of an outward-moving CME will result in a characteristic frequency- and time-dependent signature in the reflected signal. The rich information inherent in this measurement could open an entirely new window on CME studies, yielding their angular distribution, ranges, and line-of-sight velocities. Figure 10 shows that combining the radial velocity obtained from the Doppler shift with the trans-

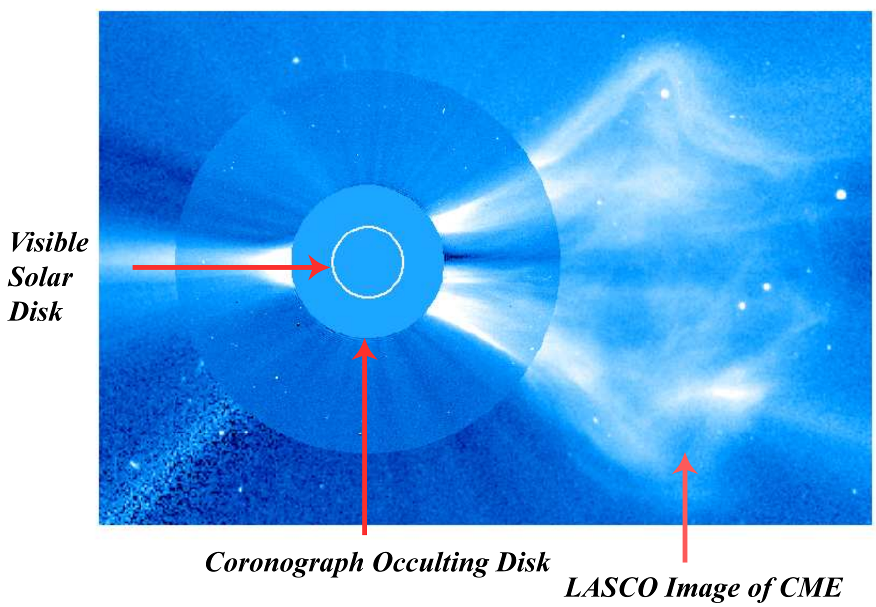

Fig. 8—A LASCO coronograph image of a transversely directed CME. Coronograph images are most effective for determining transverse motions of CMEs. Figure courtesy of NRL, Code 7600.

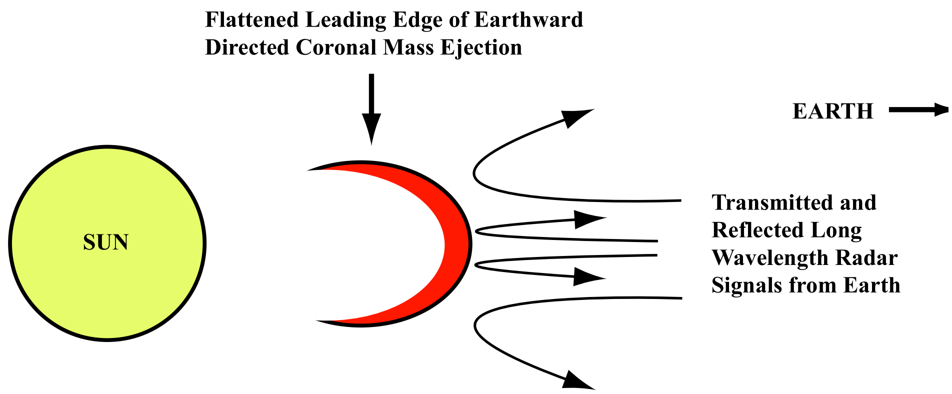

Fig. 9—Basic geometry of solar radar. Low frequency signals transmitted from Earth in the 10–80 MHz range will be reflected off the solar corona at an altitude corresponding to the relevant plasma frequency. An outward moving CME will impose a Doppler-shifted signature on the reflected signal that can be used to detect and image the CME.

verse velocity obtained from imaging is required to determine the CME total velocity vector. This would allow for accurate predictions of CME Earth-arrival times. Sufficient transmitting facilities now exist (Arecibo Observatory, over-the-horizon radars that are no longer required for military purposes), but adequate receiving facilities are needed for such a project.

Currently, space-based coronographs are used to detect and track CMEs (Figure 8). However, space-borne white-light coronagraphs detect the Thomson-scattered light from the CME material and therefore are less sensitive to structures propagating at large angles out of the plane of the sky, such as Earth-directed CMEs. An array of coronographs in the Earth's orbit could provide the stereoscopic view to determine this information, but at significant cost and a limited, somewhat unpredictable lifetime. A cheaper and more reliable low-frequency radar system (incorporating the LWA as its imaging receiver) offers a great cost advantage over such space-based CME monitoring schemes.

Aside from the macroscopic physics of direct interest to the space weather program, there is great potential in unraveling the microscopic physics of the solar radar scattering mechanism. An understanding of this mechanism is key to solving the puzzles of the spectral shape, the large Doppler spread, the Doppler shift, and the variation in solar radar cross section. Various mechanisms have been suggested, including turbulence in the local medium (Kundu 1965), fluctuations in the altitude of the plasma resonance level due to electron density fluctuations in the solar wind (Ishimaru & Woo 1978), ion acoustic waves (Gordon 1968), and coherent lower hybrid waves (Wentzel 1981). The possibility of coherent coronal plasma waves is especially intriguing as it is a topic of current interest, and a search for such waves was included in the observing program for the Solar and Heliospheric Observatory (SOHO) spacecraft (DeForest 1996).

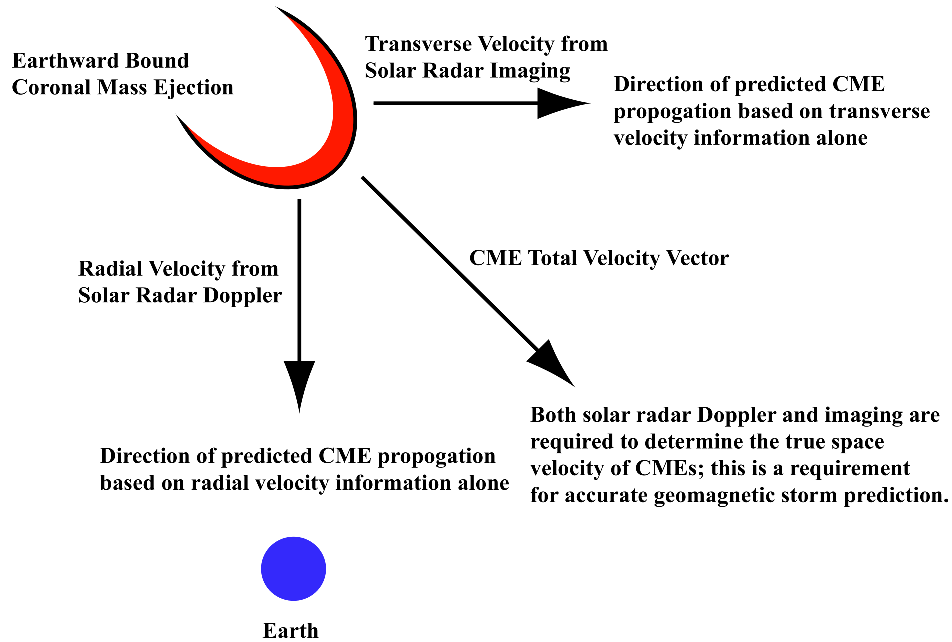

Fig. 10—A schematic illustrating that both Doppler-determined radial velocities and transverse velocities acquired from imaging are required to determine accurately the Earth arrival time of a coronal mass ejection. With a typical velocity of 200–800 km s^{-1}, a typical CME requires about three days to reach the Earth after its formation at the Sun.

Once the microphysics is understood, solar radar could become a probe of the solar plasma on a par with the modern coherent and incoherent radars used to probe the earth's ionosphere. In particular, the astonishingly accurate plasma physical theory of incoherent scatter radar has allowed a detailed and productive study of our nearest space plasma in a way undreamed of before its discovery. A similar scientific potential may be hidden in the coronal scattering mechanism.

If the LWA were located at the VLA site, Arecibo Observatory would provide an excellent location for a transmitter to conduct bi-static solar radar experiments. The National Astronomy & Ionosphere Center conducted solar radar observations in the 1960s (Parrish 1968) and has assisted in developing a preliminary engineering design for a frequency agile solar radar transmitter, illustrated in Figure 11, which would upgrade Arecibo with the transmitting power required to conduct bistatic imaging solar radar studies with the LWA located in the southwestern United States.

5.2 Solar Science

The central portion of the LWA would make an excellent multi-frequency radioheliograph that could be used to continue the solar observations pioneered by the Culgoora and Clark Lake radio telescopes in the 1970's and 1980's. The decommissioning of these instruments has severely handi-

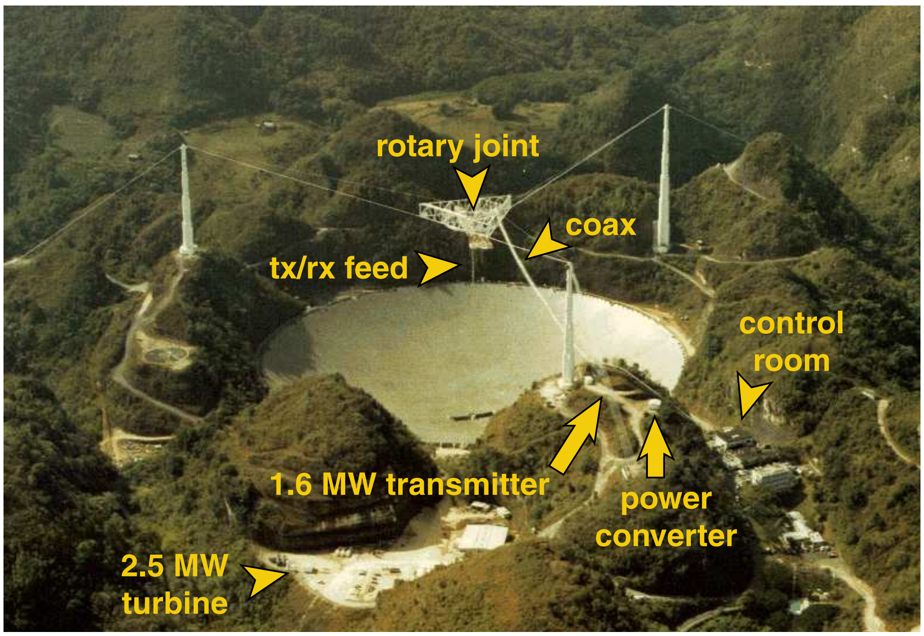

Fig. 11—Key elements of an imaging solar radar transmitter at Arecibo. Transmitter power would be 1.6 MW CW with an antenna gain of 38.2 dbi at 46.8 MHz. Bistatic Arecibo-LWA imaging solar radar observations would be possible for a period of up to 2.6 hr centered on local (Arecibo) noon for a southwestern US LWA location.

capped solar radio astronomy. At present, there is no solar–radio-imaging capability at frequencies below roughly 150 MHz anywhere in the world. Also, there is only one radioheliograph (Meudon, France) that can provide simultaneous spectral and (limited) spatial information for frequencies 160–600 MHz. Observations with the central portions of the LWA could provide important insight in the physics of the solar corona, such as:

- Recent results from joint radio–white-light observations (e.g., Maia et al. 1999) suggest that low-frequency radio observations can provide unique information on the initial CME stages, such as the coronal structures involved, speeds, densities and the sites of particle acceleration.
- In the past, instrument sensitivity has prevented reliable imaging of the quiet solar corona at low frequencies. LWA solar maps will permit high quality density measurements of various coronal structures (e.g., streamers) and the monitoring of the long term variability of the outer corona.
- The improved resolution and sensitivity of the LWA could allow imaging of certain structures within the CME itself (e.g., plasmoids, moving Type IV bursts). With the help of the radio spectrum, one can derive the magnetic field in these structures. Such information is crucial in understanding the development and subsequent propagation of CMEs but has been sketchy or missing altogether so far.
- The LWA will be able to study Type III bursts in the outer corona in detail and at a level of sensitivity far greater than in the past. This should shed light on energy release in the outer corona. The LWA will also be able to study Type II radio bursts, which are driven by magnetohydrodynamic shocks, further elucidating the relationship between coronal shocks and interplanetary shocks.
- The combination of the LWA with spaced-based solar radio instruments that operate at lower frequencies than the LWA (e.g., WIND/WAVES, Ulysses, STEREO) will permit the thorough study of the propagation of coronal material through the interplanetary medium to the Earth which can contribute not only to solar but to the magnetospheric physics as well.

In addition to providing detailed observations of solar nonthermal emission at unprecedented angular resolution, scattering measurements towards background sources offer an excellent opportunity to study the structure of turbulence in the solar corona and interplanetary medium. Previous occultation studies below 100 MHz have been limited to using the Crab pulsar as a background source. The LWA should provide access to hundreds or even thousands of background sources with which to probe the solar corona and foreground heliosphere on a routine basis as well as achieve the angular resolution required to properly complement higher frequency (e.g., 330 MHz VLA) studies.

Chapter 6

Coherent Emission Sources

High–brightness-temperature emission at long wavelengths is widely assumed to result from coherent emission processes. The Sun, Earth, Jupiter, and pulsars are good examples of objects that radiate via such processes. Coherent emission occurs most readily at long wavelengths because the size of the region from which coherent emission occurs must be smaller than the wavelength—long wavelengths allow for large regions and large numbers of particles. Plasma processes seem a natural means of producing coherent radiation. If so, coherent radiation is intimately coupled to the magnetoionic parameters of the emitting plasma—the plasma frequency, the gyrofrequency, and the collision frequency—and carries a wealth of information concerning the structure of the plasma source. In addition to known sources of coherent emission discussed below, the LWA may also identify new classes of coherent emitters, such as cyclotron maser emission from extrasolar planets (Dulk et al. 1997; Farrell et al. 1999).

6.1 Pulsars

Pulsars were discovered using a low-frequency instrument (81 MHz, Hewish et al. 1968), and most searches for radio pulsars to date have searched for dispersed, pulsed emission at frequencies of 400–1400 MHz. Alternate search techniques will need to be employed at lower frequencies, as pulse broadening from interstellar scattering will become increasingly important. At 100 MHz only nearby pulsars—those with dispersion measures DM $\leq$ 100 pc cm^{-3}—will suffer pulse broadening less than 1 s and be seen as sources of pulsed emission; at 30 MHz only a handful of the very nearest pulsars, DM $\leq$ 10 pc cm^{-3}, will be seen as sources of pulsed emission (Cordes 1990).

The LWA could serve as a useful pulsar search instrument by searching for sources having pulsar-like characteristics, other than pulsed emission. Since pulsars generally, and millisecond pulsars in particular, have steep spectra, compact steep-spectrum sources would be excellent candidates for deep, higher-frequency periodicity searches. The prototypes of this search technique were the Clark Lake Radio Observatory observations of 4C21.53 and M28, which ultimately led to the identification of the first known millisecond pulsars (Erickson & Mahoney 1985; Mahoney & Erickson 1985; Figures 12 and 13). More recently, Navarro et al. (1995) discovered the millisecond pulsar PSR J0218+4232 using similar techniques. A search for compact steep-spectrum sources would also be less likely to select against the following classes of pulsars: distant, highly scattered pulsars (Lazio et al. 1999); sub-millisecond pulsars; and pulsars in tight binaries—objects for which there have been serious selection effects in most existing surveys.

Current design goals for the LWA are that it would be capable of detecting pulsars with

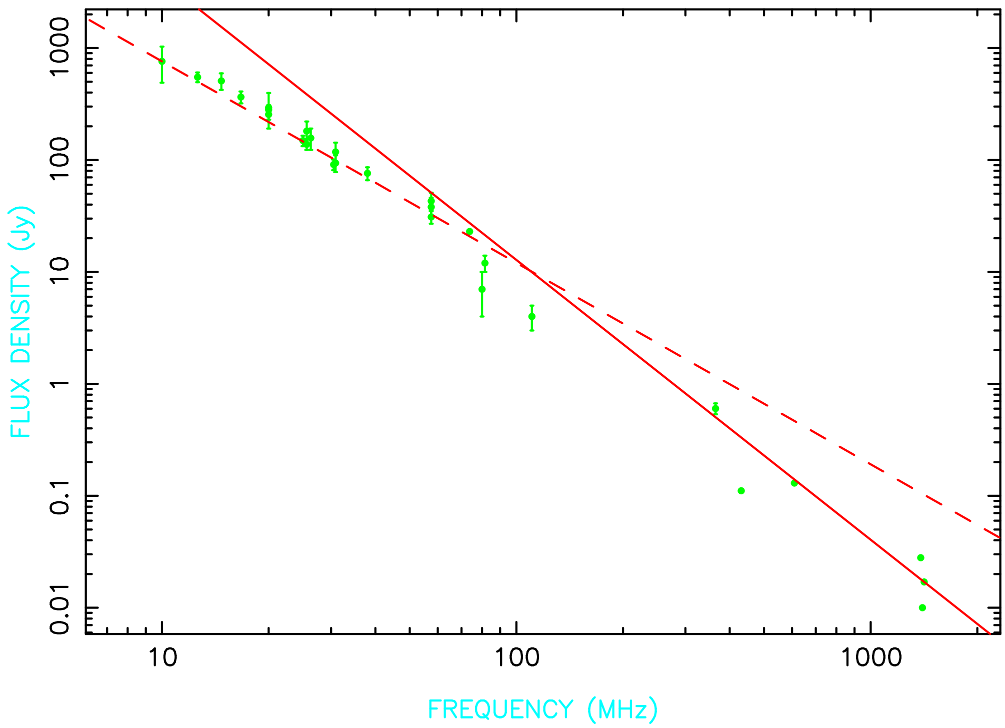

Fig. 12—The low-frequency spectrum of the millisecond pulsar PSR B1937+21. Data are from Erickson & Mahoney (1985). The solid line shows a spectrum with a spectral index of −2.5, and the dashed line shows a spectrum with a spectral index of −1.8.

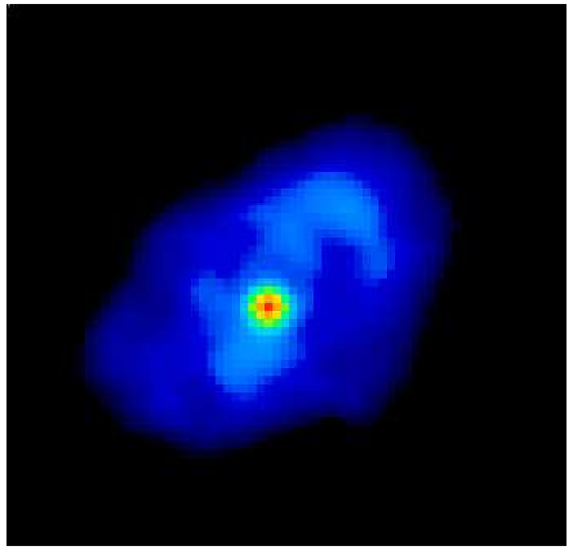

Fig. 13—The Crab Nebula and pulsar at 74 MHz

80 MHz peak flux densities of 5 mJy, assuming a 10% duty cycle. (For comparison a recent 80 MHz *periodicity* survey by Shrauner et al. 1998 had a sensitivity of 200 mJy.) The equivalent 400 MHz flux-density sensitivity, assuming a typical pulsar spectrum of -1.6, is 0.4 mJy, approximately an order of magnitude better than then recent Parkes southern-hemisphere pulsar survey (Manchester et al. 1996; Lyne et al. 1998), which found a total of 100 previously unknown pulsars. The pulsar luminosity function[1] is $dN/d(\log L) \propto L^{\beta}$ with $\beta \approx -1$. Thus, we anticipate that a survey with the LWA could increase the number of known pulsars by 500–1000—an increase of 50–100%.

The estimate of the number of pulsars that could be detected by the LWA (as well as the estimate of the total number in the Galaxy) is affected by the faint end of the luminosity function. There are indications that this luminosity function begins to turnover in the range 0.3–1 mJy kpc^2 (Dewey et al. 1985; Lyne et al. 1998), though current pulsar surveys also become incomplete near luminosities of 10 mJy kpc^2 (see also Tauris et al. 1994). The LWA's ability to detect faint pulsars would aid in assessing the extent to which this low-luminosity turnover is real.

The design of the LWA is also ambitious enough that it would probably be sensitive to pulsars in nearby galaxies. For instance, pulsars with luminosities in excess of 10^2 mJy kpc^2 (and spectral indices of -1.6) would have 100 MHz flux densities of 1 mJy at the distance of M31. (Within 1.5 kpc of the Sun, Lyne et al. [1998] find nearly ten pulsars that are bright enough.) For comparison, only a handful of pulsars are currently known outside the Galaxy, and these are in the Large and Small Magellanic Clouds (distance ≈ 0.05 Mpc).

The presence or absence of low-frequency emission from pulsars can also serve as a powerful constraint on models of the pulse emission process. A recent example has been the claimed de-

[1]The luminosity is $L_{400} = S_{400} D^2$, where S_{400} is the 400 MHz flux density in mJy and D is the distance in kpc.

tection of pulsed emission from the 237 ms gamma-ray pulsar Geminga at frequencies between 40 and 100 MHz (Kuz'min & Losovskii 1997a; Kuz'min & Losovskii 1997b; Malofeev & Malov 1997; Shitov et al. 1997; Shitov & Pugachev 1997; Vats et al. 1997). Subsequent attempts to confirm these claims have not been successful (35 MHz, Ramachandran et al. 1998; 74 MHz, Kassim & Lazio 1999). Nonetheless, the discovery of a pulsar that radiated strongly at frequencies $\nu \approx$ 100 MHz but not at higher frequencies could provide an example of a nearly aligned rotator whose emission mechanisms are different than those of the typical pulsar (Gil et al. 1998; Malov 1998).

6.2 Extrasolar Planets

Jupiter emits intense, coherent bursts of radiation at decameter wavelengths (Carr & Wang 1990) and has been detected recently with the VLA 74 MHz system (I. de Pater 1999, private communication). It has often been suggested that Jupiter-like planets orbiting other stars might be detectable by decametric observations of similar emission. Such planets, however, would have to radiate at levels several orders of magnitude greater than Jupiter in order to be detectable. At a distance of 10 pc, Jupiter's bursts would be at the 10 μJy level.

The Jupiter-like extrasolar planets that have recently been identified are generally larger and closer to their stars than Jupiter, making it likely that they may also be considerably more active in the decametric wavelength regime. Schaefer et al. (1999) have proposed that Jovian planets close to their primary may produce an RS CVn-like phenomenon in which the magnetic fields of the star and planet would become tangled. Reconnection events would then accelerate particles producing LW radio emission. In support of this model, they have identified nine solar-type stars that have been observed to undergo optical flares with energies of 10^2–10^7 times larger than those on the Sun.

An alternate mechanism would be cyclotron-maser emission from extrasolar planets. Farrell et al. (1999) recently estimated coherent cyclotron emission levels from extrasolar planets using scaling laws for the strength of planetary magnetic fields and radio emission for the planets in our own solar system. In our solar system, planets with substantial magnetic fields are also in continuous interaction with the local solar wind, which efficiently creates electric currents at their magnetospheric boundaries. These current ultimately deposit a portion of their energy in the auroral region, thereby generating the visible aurora and auroral radio emission. At Earth, Jupiter, and Saturn, the cyclotron emission level is strongly correlated with the character of the solar wind.

In the power estimates of the cyclotron radiation from extrasolar planets, it was assumed that there is an analogous stellar wind-magnetospheric interaction. The radio power from a planet orbiting a Sun-like star will then scale as

$$P \sim w^{0.8} M^{1.3} d^{-1.6}, \tag{1}$$

where w is the planetary rotation period, M is the planet mass, and d is the star-planet distance. Table 14 summarizes the expected flux levels from a number of known extrasolar planets. The estimates indicate that the best candidate for detection by the LWA of solar wind-driven cyclotron emission is τ Bootes, with an expected median amplitude of about 2 mJy at 28 MHz, an intensity level many decades below the current limit of detectability. However, planetary radio sources are exponential amplifiers, and arithmetic increases in stellar wind speeds correspondingly increase power levels geometrically. Thus, in extreme conditions, the estimates for extrasolar sources could be a factor of 100–1000 times higher, becoming closer to a detectable level even with current equipment.

Fig. 14—Estimated Cyclotron Maser Emission Levels from Extrasolar Planets

Star	Frequency Range of Emission (MHz)	Flux Density (mJy)
51 Peg	0.2–2	0.039–390
ν And	0.3–3	0.024–240
55 Cnc	0.1–1.6	0.015–150
ρ CrB	8–77	0.0013–13
16 Cyg B	15–140	3×10^{-5}– 0.3
47 UMa	42–403	4×10^{-5}– 0.4
τ Boo	9–84	0.22–220
70 Vig	175–1700	2.3×10^{-4}– 2.3
HD 114762	351–3400	1.5×10^{-4}– 1.5

Detection of such cyclotron emission would allow constraints to be placed on various parameters of the planet, such as the strength of its magnetic field and the presence of any close, large satellites. A search for cyclotron-maser emission at 330 MHz has been conducted (Dulk et al. 1997), and a search using the new 74 MHz VLA system is underway. The increased sensitivity of the LWA would increase the possibilities of detecting any such planets and improve constraints inferred from such detections.

Chapter 7

Surveys and Serendipitous Discoveries

Most existing radio sky surveys have been made at relatively low frequencies (e.g., the Cambridge surveys). From these surveys come both serendipitous discoveries (e.g., pulsars) and the catalogues of sources used for high-resolution mapping at high frequencies. Serendipitous discoveries often provide the greatest opportunities for advances in our understanding of the physics of astronomical objects. An excellent recent example is the 6C survey discovery of the extraordinary jet in NGC6251. The LWA would be an excellent survey instrument which can be "expected" to uncover unexpected classes of objects. The array's sensitivity will be sufficient to allow source number counts at decametric frequencies where synchrotron aging is negligible but where cosmological tests have not yet been attempted. The capability to image a large field quickly and at high angular resolution and sensitivity would allow for efficient studies of variable and transient radio source populations, for example at the Galactic center (Zhao et al. 1992).

Chapter 8

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Chapter 9

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